How Empty is Empty?

Weak-Signal Spectrum Survey Measurements and Analysis for Cognitive Radio

Christopher R. Anderson and Charles B. Cameron
(Electrical and Computer Engineering Department
United States Naval Academy, Annapolis, MD 21402
{canderso, cameronc}@usna.edu)

ABSTRACT

Spectrum sensing cognitive radios are an emerging technology that promises greater efficiency in utilizing the available wireless spectrum. In particular, spectrum-sensing cognitive radios provide the ability to search for and utilize an unoccupied portion of the wireless spectrum during periods of time when the incumbent user is inactive. A key requirement to operating cognitive radios, therefore, is accurately and reliably identifying unutilized frequency bands, even when those bands may contain extremely weak signals.

In this paper, we present initial measurement results from two spectrum occupancy studies conducted in and around Annapolis, Maryland and the US Naval Academy in the frequency range between 700 MHz and 6 000 MHz. At the highest resolution, the measurement system had a noise floor of -133 dBm, allowing it to record signals that were 10–30 dB weaker than those previously reported in the literature. Analysis of the measurement results indicate that spectrum utilization increases exponentially as the receiver's noise floor decreases. Additionally, variations with time, frequency, and receiver threshold are observed. These results imply that, in order to provide reliable detection of incumbent users, cognitive radios will require sensitive receivers and accurate detection algorithms.

1. INTRODUCTION

Over the past decade, rapid growth in wireless communications has resulted in steadily increasing demand for a perpetually scarce resource: access to the wireless spectrum. At present regulatory agencies have primarily been in charge of allocating this scarce resource by issuing licenses that authorize exclusive use of a portion of the spectrum. More recently, in an attempt to meet the demand for mass-market commercial wireless technologies, regulatory agencies have designated certain bands as unlicensed, where users that meet the power and frequency requirements of the band are free to operate, regardless of whether they may cause other users in the band to suffer interference or deleterious performance.

The introduction of spectrum-sensing Cognitive Radio (CR) by Mitola [1] is widely heralded as a means to overcome the limitations on spectrum access imposed by the current licensed/unlicensed model. A spectrum-sensing CR is able to search for an underutilized band of the spectrum, which it can opportunistically reclaim during periods of inactivity, vacating the frequency band upon the return of the incumbent user. Because spectrum-sensing CR is an overlay approach (i.e., it must coexist with the incumbent users), its overall success is highly dependent on its success in (a) locating unutilized spectrum and (b) detecting the return of an incumbent user.

In order to investigate the feasibility of CR, a number of studies have examined the amount of unutilized or underutilized spectrum that might be available to CR. [2]–[5] Many of these studies focus only on signals with power above approximately -100 dBm to -110 dBm, essentially excluding anything below those levels from their analysis. A narrowband receiver—one with bandwidth less than 100 kHz—with a typical noise figure of less than 5 dB, however, will have a noise floor in the -130 dBm to -120 dBm range and will be able to achieve good performance even when the received signal power is in the -120 dBm to -110 dBm range. Cognitive radios that are designed only to look for signals above -110 dBm have the potential to cause significant interference to incumbent narrowband users whose received signal levels are in this power range. As a result, CR has attracted strong criticism from organizations such as the television broadcast industry, who have expressed concerns that their signals may be affected adversely [6].

2. EXPERIMENTAL SETUP

2.1 Measurement System

A basic block diagram of the spectrum occupancy measurement system is shown in Fig. 1. In order to accurately record extremely weak signals, the measurement system utilized an ultra-low noise Miteq AFS3 amplifier with a measured 1.4 dB noise figure (LNA in the figure). To

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **OCT 2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE
How Empty is Empty? Weak-Signal Spectrum Survey Measurements and Analysis for Cognitive Radio

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
United States Naval Academy,Department of Electrical and Computer Engineering,Annapolis,MD,21402

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Proceedings of the Software Defined Radio Technical Conference and Product Exposition (SDR '08), Washington, DC, USA, 26?30 October 2008

14. ABSTRACT
Spectrum sensing cognitive radios are an emerging technology that promises greater efficiency in utilizing the available wireless spectrum. In particular, spectrum-sensing cognitive radios provide the ability to search for and utilize an unoccupied portion of the wireless spectrum during periods of time when the incumbent user is inactive. A key requirement to operating cognitive radios, therefore, is accurately and reliably identifying unutilized frequency bands, even when those bands may contain extremely weak signals. In this paper, we present initial measurement results from two spectrum occupancy studies conducted in and around Annapolis, Maryland and the US Naval Academy in the frequency range between 700 MHz and 6 000 MHz. At the highest resolution, the measurement system had a noise floor of −133 dBm, allowing it to record signals that were 10?30 dB weaker than those previously reported in the literature. Analysis of the measurement results indicate that spectrum utilization increases exponentially as the receiver?s noise floor decreases. Additionally, variations with time, frequency, and receiver threshold are observed. These results imply that, in order to provide reliable detection of incumbent users, cognitive radios will require sensitive receivers and accurate detection algorithms.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

minimize the overall system noise figure, the amplifier input was connected directly to the output of a wideband biconical antenna. The output of the amplifier was then connected to either an Anritsu MS2692A or MS2724B spectrum analyzer. Finally, a laptop computer was utilized to download and record data from the spectrum analyzer, and Matlab® was utilized to post-process and analyze the data.

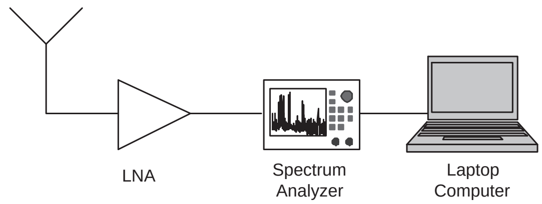

Fig. 1. A block diagram of the Spectrum Occupancy Measurement System.

2.2 Description of Measurement Procedure and Locations

Three different types of spectrum occupancy measurements were recorded in several locations around Annapolis, Maryland as well as the United States Naval Academy (USNA):

- Short-term low-resolution measurements from the Annapolis area using a low-to-ground antenna.
- Long-term high-resolution measurements from the USNA clock tower.
- Short-term low-resolution measurements from the USNA clock tower.

2.2.1 Short-term Low-resolution Annapolis Area Data

For the short-term measurements in the Annapolis area, four different sites were chosen to provide some diversity in the measurement environments:

- The seawall at the United States Naval Academy (USNA) in Annapolis, Maryland, next to the Severn River ($38.9864°$ N, $76.4842°$ W).
- LeJeune Hall at USNA near the gate to downtown Annapolis ($38.9775°$ N, $76.4814°$ W).
- Lee Airport, a small airport in Edgewater, Maryland, just south of Annapolis ($38.9411°$ N, $76.5639°$ W).
- Baltimore Washington International Airport (BWI) in Baltimore, Maryland ($39.1867°$ N, $76.6544°$ W).

At each of these measurement sites, the measurement system antenna was placed in an open area free from any obstructions that could cause shadowing, at a height of 1.5 m above the ground, and at least 100 m away from any visible transmitting antenna. For every frequency range, 10 spectrum analyzer sweeps were recorded over a 15-minute time period. Measurements were recorded using the MS2692A in each of three frequency ranges: (a) 800–1300 MHz, (b) 1300–2000 MHz, and (c) 2000–2500 MHz.

To ensure that even the weakest of signals was recorded, the spectrum analyzer was configured to utilize a 10 kHz resolution bandwidth and record 1601 points in each frequency range, resulting in a measured noise figure of 1.9 dB for the entire system. To establish the noise floor for the measurement system, the antenna was disconnected and replaced with a $50\,\Omega$ load. Then a series of traces were recorded in each frequency range, resulting in a measured noise floor of -135 dBm.

Measurement results from each frequency range were concatenated together to form a composite data set in order to facilitate analysis over the entire 800–2 500 MHz frequency range. Additionally, results from all four sites were pooled together into a single composite short-term measurement data set.

2.2.2 Long-term High-resolution USNA Clock Tower Data

For both the long-term high-resolution and short-term low-resolution measurements, the measurement system was installed on the upper walkway of the Mahan Hall clock tower at USNA, for a height above ground of approximately 30 meters. The antenna was installed to have a $270°$ field of view of the Academy and downtown Annapolis (with the remaining $90°$ effectively blocked by a tower support).

When performing the high-resolution measurements, data were recorded in 2.0 MHz segments across a 700–3 000 MHz block. Measurements were repeated every three hours for a period of seven days. The spectrum analyzer was configured to utilize a 3 kHz resolution bandwidth and record 551 points in each 2 MHz segment, resulting in a measured noise figure of 2.2 dB (slightly higher than the short-term configuration due to the use of a different spectrum analyzer and a longer cable between antenna and analyzer). To determine the noise floor, the antenna was disconnected and replaced with a $50\,\Omega$ load, resulting in a measured noise floor of -133 dBm. Measurement results from each 2 MHz segment were concatenated together to form a composite data set so that analysis could be performed on the entire 700–3 000 MHz frequency range.

2.2.3 Short-term Low-resolution USNA Clock Tower Data

To record the short-term measurements, at the completion of a 700–3 000 MHz long-term measurement block, the spectrum analyzer was reconfigured to utilize a 3 MHz resolution bandwidth and record 551 points across a frequency range of 700–6 000 MHz. Measurements were repeated every 13–15 seconds for a 15 minute time period at the end of every long-term measurement block for the entire seven day period. For each 13- to 15-second measurement sweep, the spectrum analyzer was configured to operate in the Max Hold mode, to ensure that highly transient signals would be captured. Operating in the Max Hold mode does over-emphasize the impact of transient signals (recording them as being present

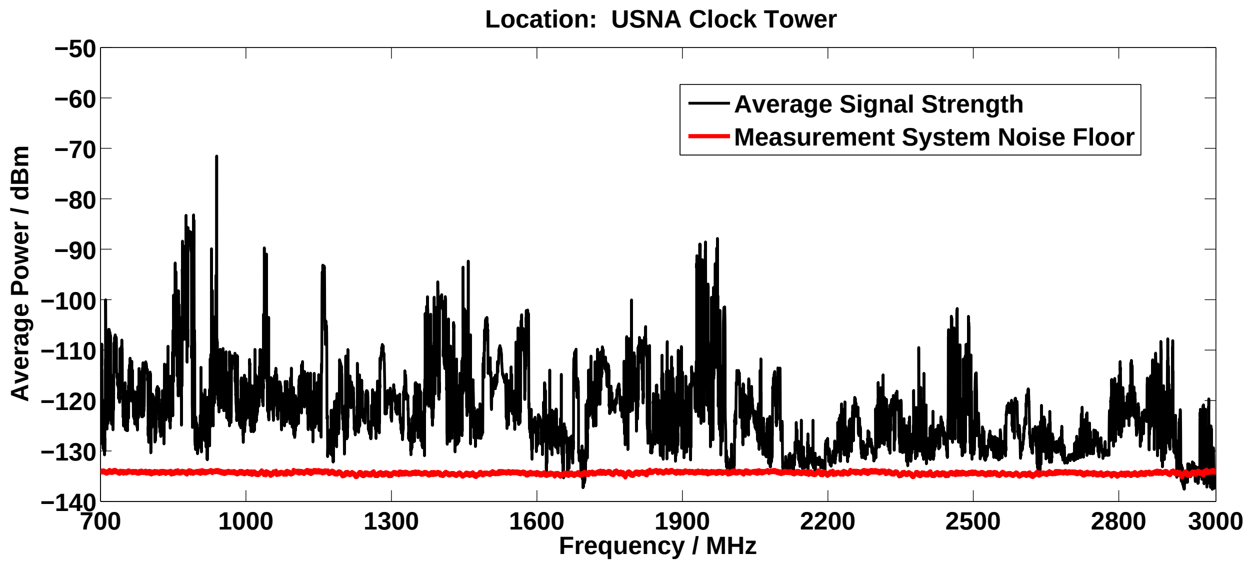

Fig. 2. Example composite spectrum recorded from the USNA Clock Tower location showing received signal power and the measurement system noise floor.

for the entire sweep, even if they were present for a very brief time period), however, repeating the measurements during the 15 minute time period helps to mitigate this over-emphasis on transient signals for any *single* measurement sweep. The system was otherwise unchanged from the high resolution measurements, and therefore maintained the noise figure of 2.2 dB, however— as a result of the higher resolution bandwidth—the noise floor for the system was measured at -102 dBm.

Collecting both long-term and short-term spectrum utilization data allows us to investigate both the significance of transient signals in the channel as well as the persistence of signals in a given frequency band. Collecting long-term data allows us to differentiate between white spectrum (very low utilization), black spectrum (very high utilization), and gray spectrum (utilization that can be high or low, depending on time-of-day). Analysis of transient phenomena, however, is important if CR is to avoid interfering with short-duration or burst transmissions.

3. Measurement Results

In this section, we investigate (a) the total spectrum utilization for each measurement set, (b) spectrum utilization as a function of frequency for each measurement set, and (c) spectrum utilization as a function of time for the high-resolution measurements. An example of a measured spectrum from the USNA Clock Tower high resolution measurements is presented in Fig. 2, illustrating both the measured spectrum and the measured noise floor of the measurement system.

3.1 Total Spectral Utilization

In this paper *total spectrum utilization* is defined as the probability that a measured signal is above a predefined power threshold (where the threshold would correspond to the noise floor of a spectrum-sensing CR) for a particular frequency range and time period. Fig. 3 presents the spectral utilization for the three measurement cases over the entire time period for which measurements were recorded and across all recorded frequencies.

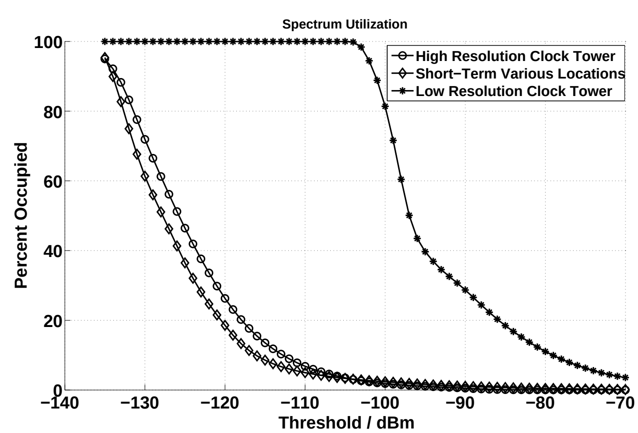

Fig. 3. Measured total spectrum utilization vs. threshold for the entire time period for which measurements were recorded and across all frequency bands and locations.

In the figure, it is important to reiterate that the low-resolution clock-tower measurement configuration had a significantly higher noise floor (-102 dBm), which means that for thresholds of less than -102 dBm, the spectrum will appear to be $100\,\%$ utilized. From the figure, we can

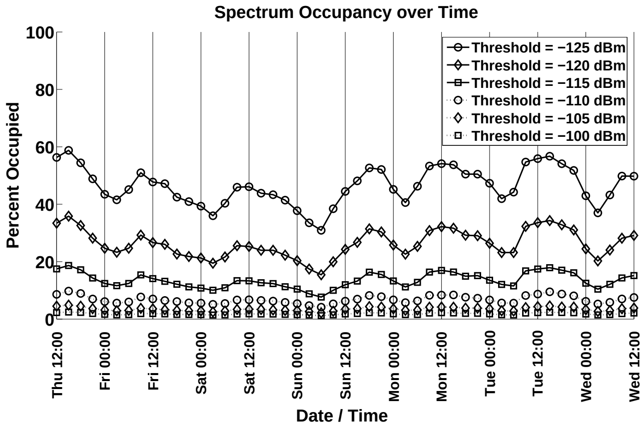

Fig. 4. Measured spectrum utilization vs. time for the long-term high-resolution clock tower measurements. Note that time is given in 24 hour format.

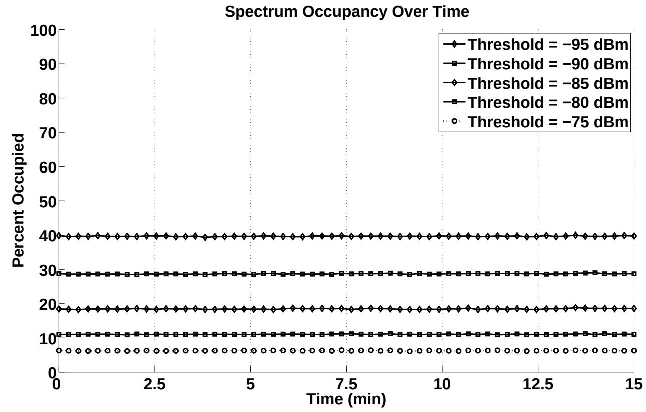

Fig. 5. Measured spectrum utilization vs. time for the short-term low-resolution clock tower measurements. The values plotted represent the pooled mean spectrum utilization across all 2 940 spectrum analyzer sweeps. Note that the standard deviation for each plotted data point is less than 1%.

observe two important trends. First, we can see that spectrum utilization increases rapidly as the threshold is decreased. This means that achieving an extremely low noise floor for CR is vitally important to detecting weak signals, and so avoiding interfering with incumbent users. For example, a CR operating with a noise floor of -110 dBm would observe that the spectrum is approximately $8\,\%$ utilized. However, the same radio with a noise floor of -125 dBm would observe a spectrum that is approximately $40\,\%$ utilized. The second observation is that utilizing the long spectrum analyzer sweep times necessary to record high-resolution measurements means that detection of highly transient signals will be missed, leading to an under-estimate of the spectrum utilization. However, the faster sweep time used in the low-resolution measurements captures both highly transient signals and electromagnetic noise (spurious emissions from transmitters, radars, etc.) and results in an overestimate of the spectrum utilization.

3.2 Spectral Utilization Over Time

To gain insight into the long-term and transient temporal variation of spectrum utilization, we investigated the probability that a signal anywhere in the recorded frequency range was above a predefined threshold at a specific point in time. For the long-term analysis, the high-resolution clock-tower measurement set was utilized, with the results shown in Fig. 4.

To determine whether transient signals had a significant impact on the spectrum utilization, a similar analysis was performed using the short-term clock tower measurements, where the results from all of the 2 940 15-minute sweeps were pooled together, and the results are given in Fig. 5. Note that we are only plotting the mean spectrum utilization, as the standard deviation for all cases was less than 1%, and deemed to be insignificant.

From Fig. 4, we can observe that spectrum utilization is roughly periodic with respect to time of day, with peak utilization occurring in the early afternoon and the nadir in utilization occurring overnight. Intuitively, these results make sense, as people generally access telecommunication services (cellular phone, wireless LANs, etc.) during the daytime. Furthermore, we can see that the trend is irrespective of the threshold chosen and that, once again, the choice of threshold has a significant impact on the observed spectrum utilization.

From Fig. 5, we observe that spectrum utilization over short time periods tends to be relatively constant, although with a significantly higher average utilization as compared to the high-resolution measurements. As with the total spectrum utilization analysis presented above, these results make sense, because recording highly transient signals will result in an overestimate of the spectrum utilization. Additionally, we observe that even when recording transient signals, the standard deviation of the measured spectrum utilization is extremely small: less than 1% in all cases. This result may be partially explained by the use of the Max Hold function on the spectrum analyzer when recording an individual sweep. However, the apparent lack of highly transient signals that disappear and reappear from sweep to sweep (resulting in large variations in the measured spectrum occupancy) is intriguing. By performing measurements during the winter months, when boating traffic around USNA is minimal, we were less likely to observe significant radar activity and, therefore, to record transient radar signals. Additionally, the lack of an extensive wireless local area network (WLAN) infrastructure on the USNA campus, as well as our locating the measurement system in the clock tower, meant the system was a long distance away from industrial, scientific, and medical (ISM) band users (Bluetooth, WLANs, etc.),

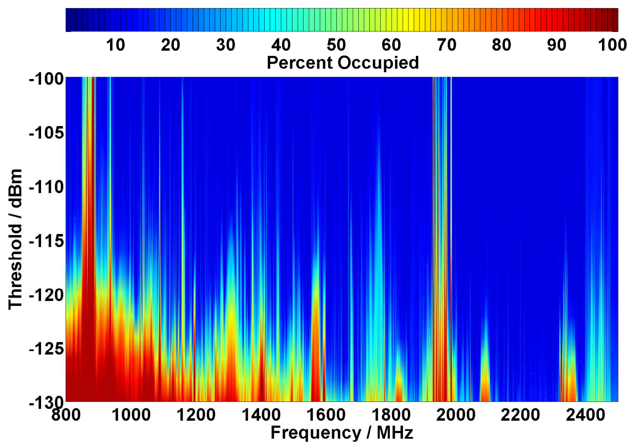

Fig. 6. Measured spectrum utilization vs. frequency for the short-term measurements recorded in the Annapolis area.

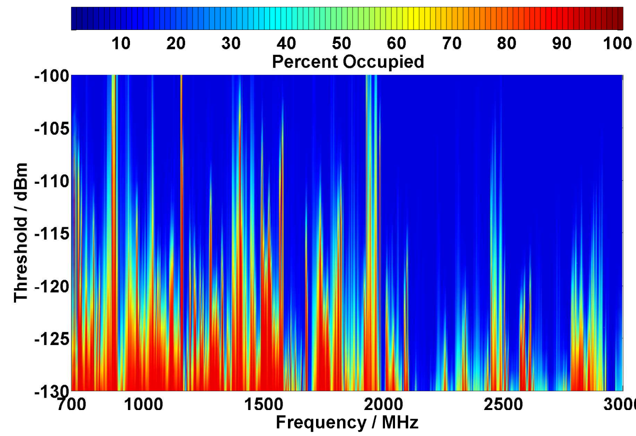

Fig. 7. Measured spectrum utilization vs. frequency for the long-term high-resolution measurements recorded at the USNA clock tower.

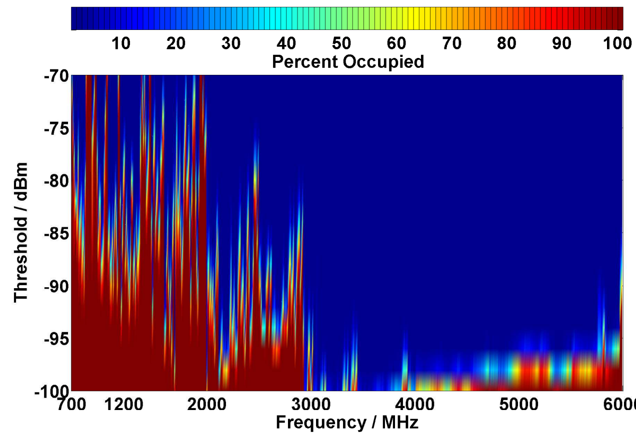

Fig. 8. Measured spectrum utilization vs. frequency for the long-term low-resolution measurements recorded at the USNA clock tower.

so transient signals in these ranges would likely have fallen below the noise floor. Further investigations at locations that are closer to highly dynamic spectrum users will be required before any significant conclusions can be drawn from these results.

3.3 Spectral Utilization Over Frequency

To determine the relationship of spectrum utilization as a function of frequency, we investigated the probability that a signal recorded at any time in the dataset was above a predefined threshold at a specific frequency. For this analysis, all three data sets were utilized, with the results as shown in Fig. 6, 7, and 8. From these figures, we can note several interesting trends. First, in all three figures, we observe high spectrum utilization at a variety of frequency bands, including the two cellular bands (824–894 MHz and 1 850–1 990 MHz), the L1 and L2 Global Position System (GPS) bands (1 575 MHz and 1 227 MHz), as well as the 900 MHz and 2 400 MHz ISM bands. Further, certain bands (such as the cellular bands) generally have very high occupancy regardless of the threshold—making these bands essentially unavailable for use by CR.

However, a number of frequency bands show almost no utilization—making them excellent candidates for spectrum-sensing CR. Furthermore, we can see that a greater percentage of the spectrum is available for use by CR at higher frequencies. This result makes sense intuitively as, for a given transmitter power level, a wireless signal will propagate farther at a lower frequency, leading to a higher observed utilization at any particular location.

4. Conclusions

This paper presented the results of a spectrum occupancy measurement campaign in and around Annapolis, Maryland in the frequency range of 700–6000 MHz. Our measurements indicate that a large number of incumbent users may be operating in these bands at very low received signal strengths of -110 dBm to -130 dBm, which is well below CR sensing thresholds previously reported in the literature. These existing users could potentially receive detrimental interference from cognitive radios unable to detect the presence of such low-power signals. Furthermore, our data suggest that as the sensing threshold is decreased, the amount of white and gray spectrum available to cognitive radio decreases very rapidly. While these results are preliminary, further measurements in more geographically diverse locations will provide a clearer understanding of the nature and power levels of incumbent users and their impact on the amount of spectrum available to cognitive radios.

References

[1] J. Mitola, “Cognitive radio: Making software defined radio more personal,” *IEEE Personal Communications*, vol. 6, pp. 13–18, August 1999.

[2] M. A. McHenry, D. McCloskey, and G. Lane-Roberts, “Spectrum occupancy measurements, location 4 of 6: Republication National Convention, New York City, New York, August 30, 2004–September 3, 2004,” Tech. Rep., August 2005.

[3] D. A. Roberson, C. S. Hood, J. L. LoCicero, and J. T. MacDonald, “Spectral occupancy and interference studies in support of cognitive radio techonolgy deployment,” in *IEEE International Workshop on SDR*, 2006, pp. 26–35.

[4] R. I. C. Chiang, G. B. Rowe, and K. W. Sowerby, “A quantitative analysis of spectral occupancy measurements for cognitive radio,” in *IEEE Vehicular Technology Conference*, 2007, pp. 3016–3020.

[5] M. Biggs, A. Henley, and T. Clarkson, “Occupancy analysis of the 2.4 GHz ISM band,” *IEEE Proceedings on Communications*, vol. 151, pp. 481–488, October 2004.

[6] National Association of Broadcasters and Association for Maximum Service Television, Inc., “Reply comments of MSTV and NAB to the OET report on the performance of prototype TV-band white space devices,” August 2007, in the matter of Federal Communications Commission ET Dockets No. 04-186 and 02-380.